Analysis of Electric Propulsion Capabilities in Establishment and Keeping of Formation Flying Nanosatellites

Eviatar Edlerman and Igal Kronhaus
Introduction

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* CubeSats have strict constraints on allowed mass, volume, electrical power, and carry only limited sensor and actuator capability

* Nanosatellite formation can increase the functionality of these satellites

* Miniaturized electric propulsion (EP) system offer an advantage over chemical propulsion thrusters by their smaller volume and mass, offer new possibilities for nanosatellite orbit and attitude control
Research Objectives

* Define typical Nanosatellite mission constraints
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* Design very low thrust EP control algorithm for long-term cluster flight

* Offer different methods of using the controller in the presence of mission constraints and while causing minimal impact on other mission tasks

* Validate these methods on a high fidelity simulation
CubeSat Constraints

* Spacecraft structure constraints
* Attitude constraints
* Electrical power constraints
* Orbital constraints

<table>
<thead>
<tr>
<th>Model</th>
<th>Mass [kg]</th>
<th>Volume [cm^3]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1U</td>
<td>1.33</td>
<td>1000</td>
</tr>
<tr>
<td>3U</td>
<td>4</td>
<td>3000</td>
</tr>
<tr>
<td>6U</td>
<td>8</td>
<td>6000</td>
</tr>
</tbody>
</table>
A requirement of pointing one of the satellite axis to a specific direction allows only one rotational degree of freedom (DOF).

* Spacecraft structure constraints
* Attitude constraints
* Electrical power constraints
* Orbital constraints
CubeSat Constraints

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Angular rate limit - 1 deg/s
CubeSat Constraints

* Spacecraft structure constraints

* Attitude constraints

* Electrical power constraints

* Orbital constraints

<table>
<thead>
<tr>
<th>Model</th>
<th>SP power [W]</th>
</tr>
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<tbody>
<tr>
<td>1U</td>
<td>10</td>
</tr>
<tr>
<td>3U</td>
<td>26</td>
</tr>
<tr>
<td>6U</td>
<td>40</td>
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CubeSat Constraints

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<tr>
<th>Model</th>
<th>SP power [W]</th>
<th>Battery capacity [Wh]</th>
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<tr>
<td>1U</td>
<td>10</td>
<td>19.24</td>
</tr>
<tr>
<td>3U</td>
<td>26</td>
<td>38.5</td>
</tr>
<tr>
<td>6U</td>
<td>40</td>
<td>77</td>
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CubeSat Constraints

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<thead>
<tr>
<th>Model</th>
<th>Production SP power [W]</th>
<th>Storage Battery capacity [Wh]</th>
<th>Consumption</th>
</tr>
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<tr>
<td>1U</td>
<td>10</td>
<td>19.24</td>
<td>• 33 % housekeeping</td>
</tr>
<tr>
<td>3U</td>
<td>26</td>
<td>38.5</td>
<td>• 33 % EP system</td>
</tr>
<tr>
<td>6U</td>
<td>40</td>
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<td>• 33 % payload</td>
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CubeSat Constraints

* Spacecraft structure constraints
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Inter satellite distance bounded by 1000 km
* Spacecraft structure constraints
* Attitude constraints
* Electrical power constraints
* Orbital constraints

Orbit height have to be higher than 600 km
Very Low Thrust Orbit Control

* Simple for implementation on real time systems
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* On off controller – constant thrust magnitude
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* Cyclic controller - required information is limited to the nearest neighbor
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* Use mean orbital elements to reduce control effort
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\[
T_i = \begin{cases} 
0 & \Delta a_{ij} \Delta \lambda_{ij} \geq 0 \\
-T_{max} \text{sign} \left( \Delta a_{ij} \right) & \Delta a_{ij} \Delta \lambda_{ij} < 0 
\end{cases} 
\]

T is a thrust command in the in-track direction
a is the semi major axis
\lambda is the argument of latitude and

\[
j = \begin{cases} 
i + 1 & i = 1, 2, 3 \ldots N - 1 \\
1 & i = N 
\end{cases} 
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a is the semi major axis
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\[ j = \begin{cases} i + 1 & i = 1, 2, 3 \ldots N - 1 \\ 1 & i = N \end{cases} \]
* Non-constrained case ensures an ideal performance of the above controller

* However in a real power constrained mission, this naive approach might cause the battery to reach high DOD values.

* We offer 4 different methods to cope with this challenge:
  * Fixed time slots method
  * Dynamic time slots method
  * Cosine Method
  * Double Cosine Method
Fixed Time Slots Method

* Divide satellite orbit to time slots

* Each time slot is dedicated for different mission

* In this example satellite collect sun during the day and perform orbit control during the night – reduce DOD values

<table>
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<tr>
<th>Sun Pointing</th>
<th>Orbit Control</th>
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Time
Fixed Time Slots Method

* Divide satellite orbit to time slots

* Each time slot is dedicated for different mission

* In this example satellite collect sun during the day and perform orbit control during the night – reduce DOD values

* Orbit can be divided to more slots based on the mission requirements

* Orbit control “duty cycle” is proportional to maximal inter-satellite distance (ISD)
Dynamic Time Slots Method

* Satellite collects data parameters from different subsystems, data that can be valuable for decision making
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* Time slots can be set based on real time collected data such as:
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  * Inter-satellite distance
  * Ground station access
  * Payload activation
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  * Inter-satellite distance
  * Ground station access
  * Payload activation
* In this case we use battery DOD status

Dynamic Time Slots Method
Cosine Method

* SP maximum power is reached when the SP are aligned with the sun vector
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* The remaining DOF can be used to bring the thrust vector as close as possible to the velocity vector

\[
\begin{align*}
\hat{z}_B &= \mathbf{s} \\
y_B &= \mathbf{s} \times \mathbf{v} \\
x_B &= y_B \times z_B
\end{align*}
\]
Cosine Method

* SP maximum power is reached when the SP are aligned with the sun vector.

* The remaining DOF can be used to bring the thrust vector as close as possible to the velocity vector.

* Analysis shows that even 20° misalignment have negligible effect on the controller performance.
Double Cosine Method

* Enhance cosine method performance by creating an additional error cone around the sun vector.

\[ P = P_0 \cos(\theta) \]
Double Cosine Method

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* Control the allowed loss in power generation
Double Cosine Method

- Enhance cosine method performance by creating an additional error cone around the sun vector.

- Control the allowed loss in power generation

- Control the allowed thrust misalignment from the in-track direction
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* Control the allowed loss in power generation

* Control the allowed thrust misalignment from the in-track direction

* Analytical expressions were developed to calculate the required orientation in real time
Numerical Simulation Setup

* FreeFlyer™ software were used as nonlinear orbit propagator that include:
  * Drag model
  * Solar radiation pressure
  * Earth zonal and tesseral potential terms
  * Moon gravity field and sun gravity field.
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* We design a simplified electric power system model and embedded it in the FreeFlyer simulation.
Case Study

* A cluster of 3 6U CubeSats
* Deployable SP model
* EP thruster create 100 µN with Isp of 1000 s and power consumption of 13 W
* Cluster initial condition are based on PSLV orbit injection scenario with radius of 620 km
Non-constrained Performance

* To create reference to the other method we define the ideal performance of the controller.
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Satellite attitude is changing according to this logic:

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<th>Thrust required</th>
<th>No thrust required</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_B = T$</td>
<td>$z_B = s$</td>
</tr>
<tr>
<td>$y_B = T \times s$</td>
<td>$y_B = s \times v$</td>
</tr>
<tr>
<td>$z_B = y_B \times x_B$</td>
<td>$x_B = y_B \times z_B$</td>
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Non-constrained Performance

![Graph showing distance over time for different distances]
* Both methods meet the mission requirements
* Dynamic time slots method have lower ISD
* Maximal ISD is proportional to the “duty cycle”
* DOD can be trade to decrease max ISD
* Allocating too much slots will damage the method performance.
* Cosine methods allow satellite to perform its primary mission while orbit control is in the background

* Eliminating hard constraints offers new control possibilities

* Double cosine method offers the lowest ISD of all other methods and power losses due to SP misalignment is negligible
Results - Double Cosine Method

* Double cosine method increases available thrust arcs while have minimal effect on other mission tasks

* Double cosine method allows large portion of thrust in the in-track direction, reducing fuel consumption and convergence time
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* It was demonstrated that the proposed methods presented here can maintain a formation of multiple nanosatellites for long periods using low power EP systems while working under real mission constraints.
Questions?